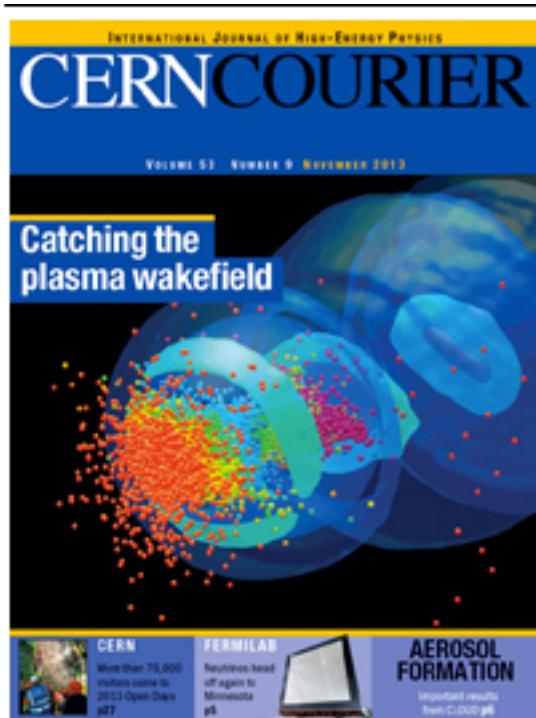


UCLA



UCLA Program on Advanced Accelerator R&D

Chan Joshi
University of California Los Angeles

With contributions from W. Mori, P. Musumeci, J. Rosenzweig
And from E200, 217 collaborations on FACET

Presented to: The Accelerator R&D Subpanel

UCLA Advanced Accelerator R&D VISION

Transformational R&D for a TeV scale e^+e^- collider

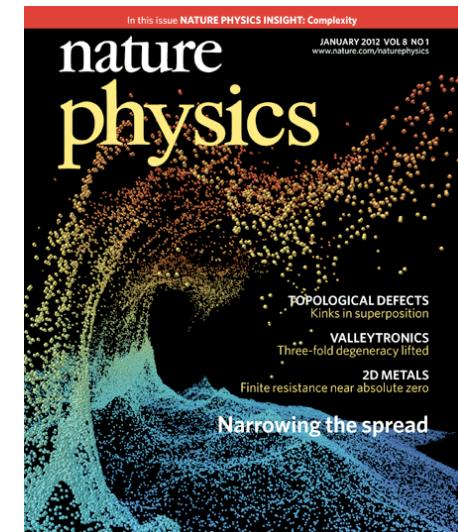


To address critical physics issues for realizing an accelerator based on advanced concepts at the energy frontier in the next decade. A by- product will be compact accelerators for industry & science

UCLA vision is well matched to P5 and NAE priorities for long range Accelerator R&D

Main Research Themes

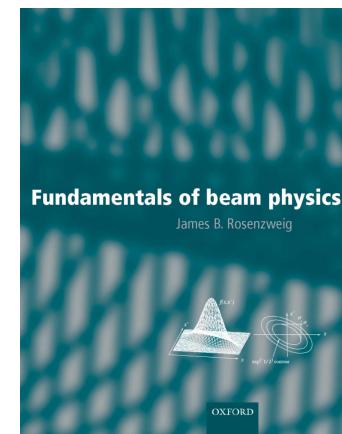
- 1) Techniques for high gradient, high efficiency acceleration of electrons and positrons using lasers, beams in the near field, far field and media and RF
- 2) Focusing of electron and positron beams with plasmas and miniature magnetic lenses
- 3) Radiation generation for photon-photon colliders, table-top Compton sources and R&D towards 5th generation light source
- 4) Acceleration of high quality ion beams using lasers for medical applications.



Highest quality H⁺
Beams using CO₂ laser

UCLA effort is comprehensive

- **Experiments:** In house facilities Neptune and Pegasus
Collaborative experiments at FACET, LLNL, ATF
(in the past at LANL and Fermilab as well)
- **Theory:** Attributable to world class beam physics , plasma physics and laser science programs
- Accelerator Physics classes: P150, P250
- Plasma Physics classes: P285A, B, C
- Laser Physics classes: EE 270, 271, 272, 273
- USPAS teaching
- **Computer Simulations:** In house GPU-based cluster, access to Titan, Hopper, Blue Waters, Edison, Mira



Student/Postdoc training integral aspect of program

- Some well known alumni in HEP labs and academia
- Many have won national awards* and doctoral theses prizes**

HEP/DOE labs

- M. Hogan (SLAC)*
- E. Colby (SLAC/DOE)
- J. England (SLAC)
- P. Muggli (MPI/Cern)*
- W. Leemans (LBNL)* **
- C. Huang (LANL)**
- J. Ralph (LLNL)
- A. Pak (LLNL)

Academia

- Katsouleas (USC → Duke)*
- Mori (UCLA)***
- Lu (Tsinghua)***
- Musumeci (UCLA)
- Umstadter (U. Michigan U → Nebraska)
- Williams (Florida A&M)**
- Kitagawa (Osaka U., Hammamatsu U)*
- Y. Sakawa (Nagoya)
- L. Silva (IST, Portugal)
- C. Ren (U. Rochester)

Basis for Evaluating Advanced Accelerator Schemes

Compact and affordable e^-e^+ collider with a few TeV CM energy-
A Grand Challenge for Engineering in 21st Century

	CLIC	Dream Scheme
Gradient	150 MV/m	1.5-15 GV/m
Efficiency	27%	50- 90 %
(Primary-Accelerated beam)		
Energy	3 TeV	5-10 TeV
Luminosity	$10^{34} \text{ cm}^2\text{s}^{-1}$	$>4\times10^{34} \text{ cm}^2\text{s}^{-1}$
Wall-plug eff	4.8% @ 3 TeV	10-15% @ few TeV

Here we consider a beam driver because the cost implications of the technology is better understood

Advanced Acceleration Schemes Explored at UCLA

Many key ideas originated at UCLA

1) Acceleration Using Plasmas (Joshi/Mori, Rosenzweig Groups)

Plasma Wakefield Acceleration, P. Chen et.al.PRL(1983), Rosenzweig et al P.R.L. 88

J. Rosenzweig et al (1990), Almost all key ideas from UCLA

Laser Plasma Acceleration, T. Tajima and J. M.Dawson PRL(1979), Joshi et al PRL (1981)

C. Joshi et al Nature 84, M. Everett et al Nature (1993),
Modena et al Nature, W. Lu PRSTAB (2007)- blowout regime
(UCLA's current effort discussed in Mike Downwe's talk)

2) Beam-driven Dielectric Acceleration (Rosenzweig) M. Thomson et al PRL(08)

3) Far Field Acceleration: Inverse FEL acceleration (Musumeci, Pellegrini)

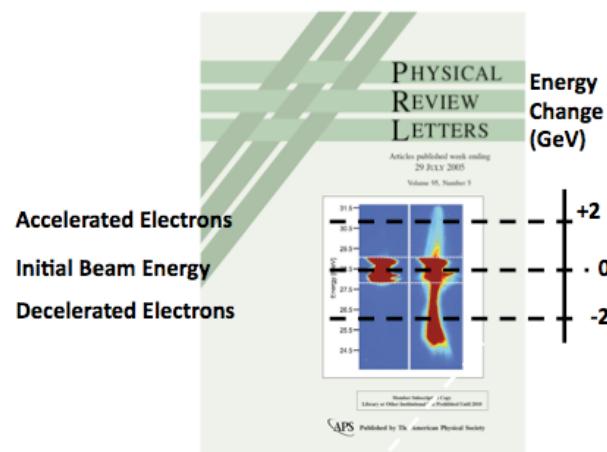
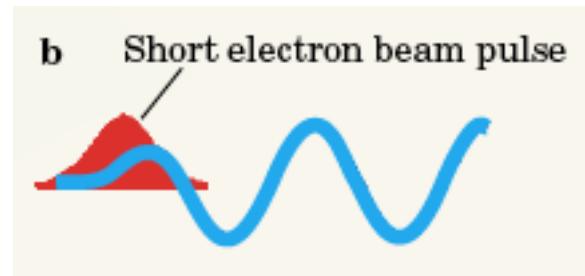
Rubric for Evaluating a New Accelerator Scheme

✓ Shown using theory, simulations and relevant experiments

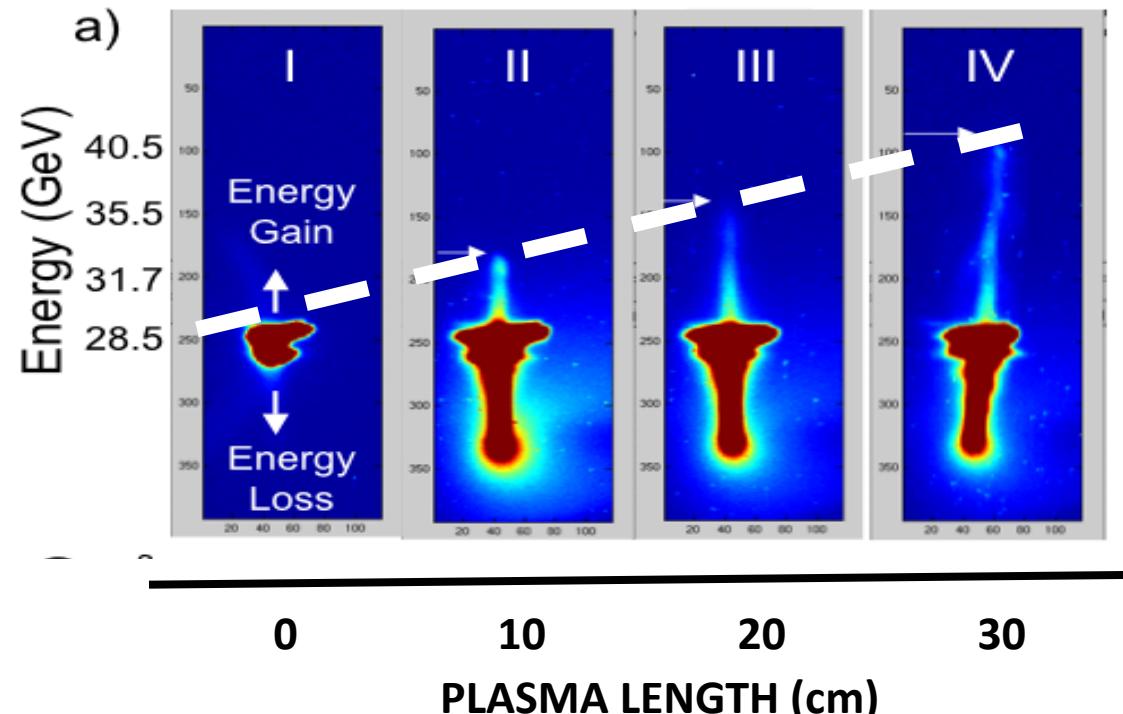
	PWFA
• Capable of High Loaded Gradient	✓
• Small Energy Spread	✓
• Significant charge	✓
• High Energy Extraction Efficiency	✓
• High rep Rate	needs demonstration
• Ultra-low emittances	FACET II
• Staging possible	needs demonstration
• Radiation loss	(γ , n_p , σ_r) scaling measured
• Repeat for positrons	Preliminary , ongoing

Team building and Collaboration key to Progress

UCLA/SLAC/USC PWFA 1998-2007

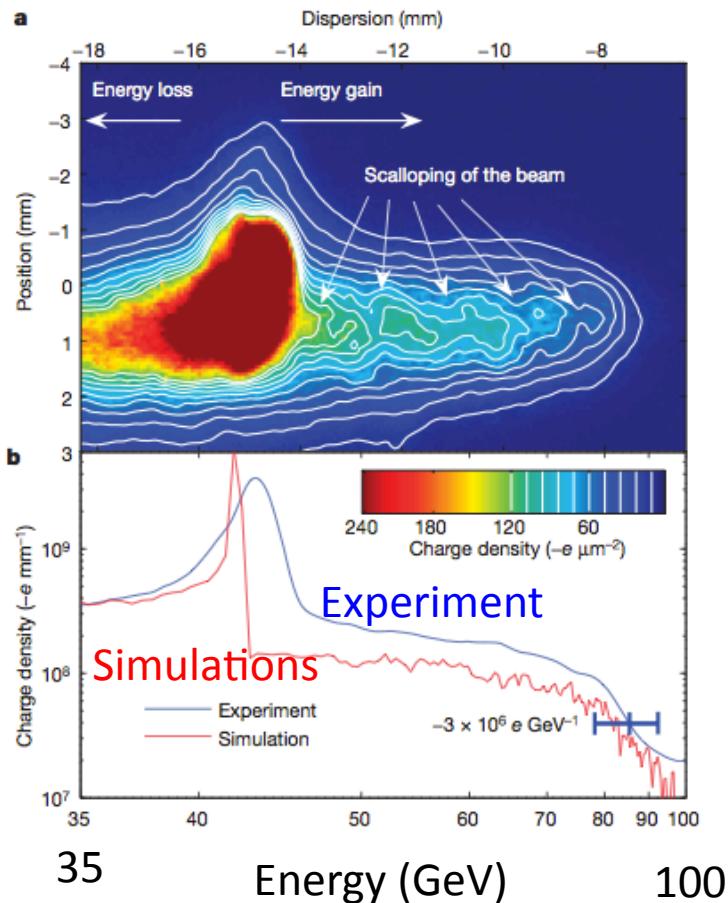


$n_e \approx 3.5 \times 10^{17} \text{ cm}^{-3}$ $L \approx 10 \text{ cm}$, $N \approx 1.8 \times 10^{10}$, $\tau \approx 50 \text{ fs}$



Beam-Driven Wakefield Acceleration from 42 GeV-85 GeV in 85 cm.

UCLA





Status of PWFA on FACET: E200 UCLA/SLAC **UCLA**

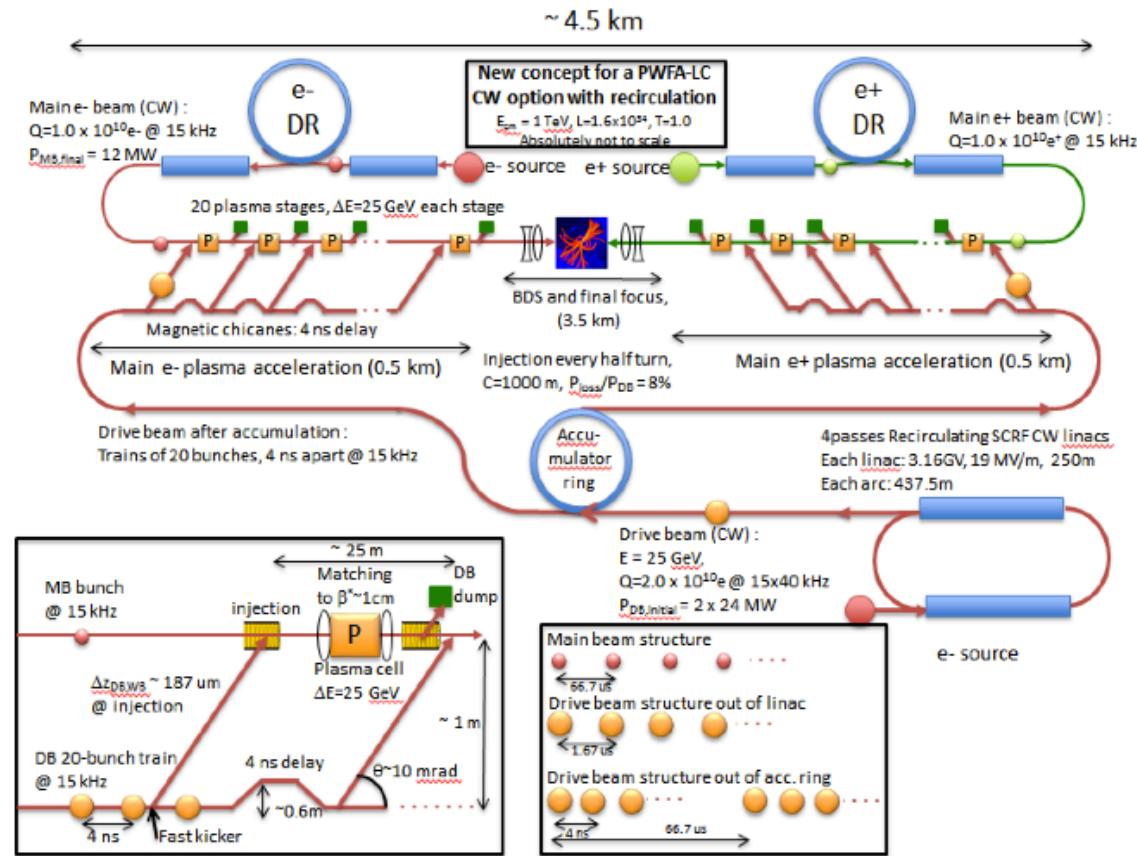
M. Litos et al Submitted for publication

Redacted because of embargo policy of the journal
Our sincere apologies...
Please contact C. Joshi if this information is needed

Multi-Stage PWFA LC: A Strawman Design

PWFA milestone now driven by collider application

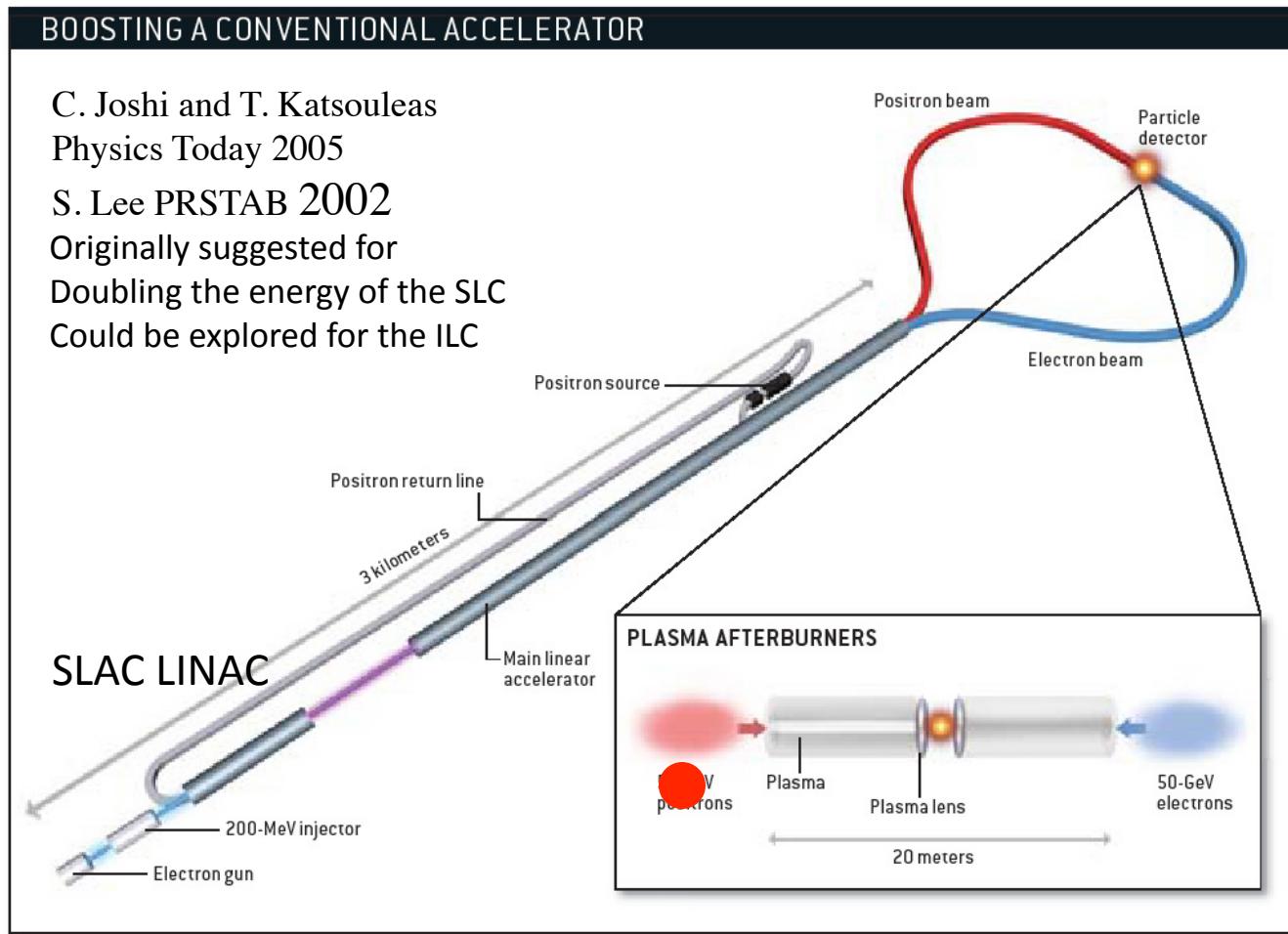
Figure 1: Layout of a 1 TeV PWFA Linear Collider



Ref: E. Adli, J. P. Dalahaye et al arXiv 1308.1145, SLAC-Pub-15426

Plasma Afterburner for a Linear Collider

An alternate application of PWFA to a linear collider



How close are we to achieving all the parameters needed for single stage of a staged-PWFA?

PWFA-LC Design study

Drive Charge(nC)	3
Charge/bunch	1.6nC
Energy/stage (GeV)	25
Efficiency	50%
Gradient (GeV/m)	7.6
Length (m)	3.3
Energy Spread (%)	1
Transformer ratio	1
Plasma Density (cm ⁻³)	2e16
Emittance (nm)	

Redacted due to
Embargo policy
Of the Journal

Contact C. Joshi
For this information

What will it take?

FACET II
FACET II (10 GeV)
1.3m plasma
Optimal loading
FACET II
Hydrogen plasma
FACET II
➤OK
➤ OK
FACETII

What about generation of ultra-low emittance beams?

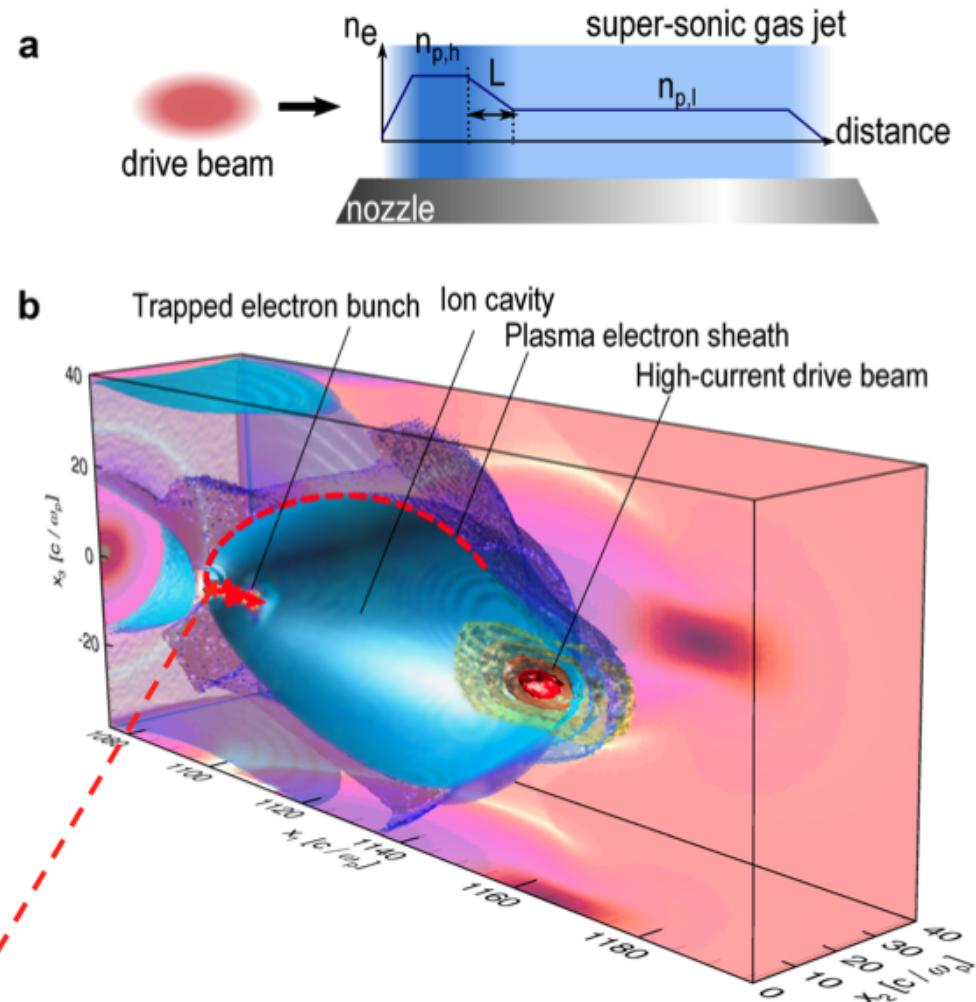
Li, Lu, Xu et al. Tsinghua U. and UCLA
H Suk et al, PRL 2001

- Need higher charge, $>3\text{nC}$
Drive beam: FACET II
- Beam-driven plasma acceleration in blowout regime can produce such beam via density transition: $\sim 1\text{nC}$
- 3D-simulation using OSIRIS

Output Beam

$\epsilon_n < 30\text{nm rad}$, $I \sim 10\text{kA}$, $\Delta E < 3\text{MeV}$,
 $B_n > 2 \times 10^{19}\text{A m}^{-2}\text{rad}^{-2}$

trapped sheath electron trajectory

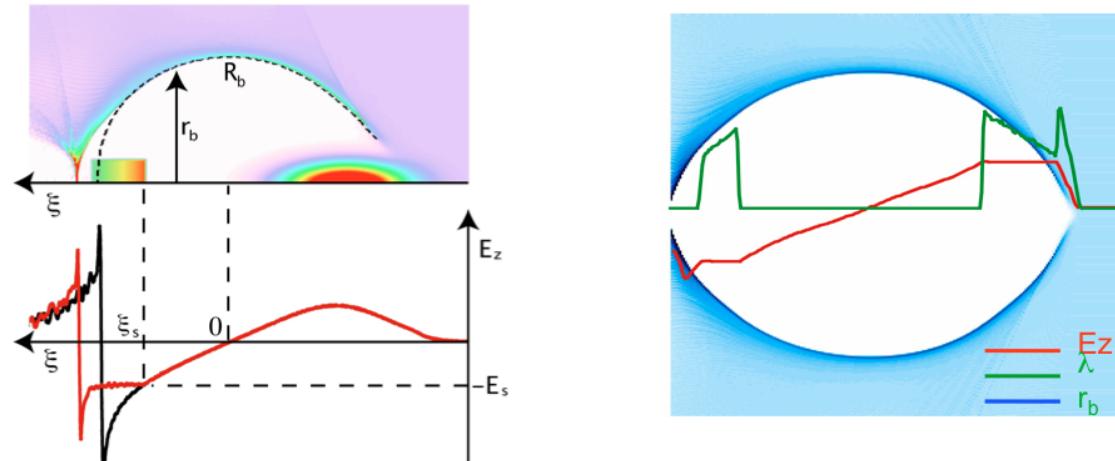


Major Effort on FACET II
Preliminary expts planned on FACET

What about Increasing Energy Transfer Efficiency from 30% to > 60%?

Drive and trailing bunch shaping can increase the efficiency

M. Tzoufras et al. PRL 2008

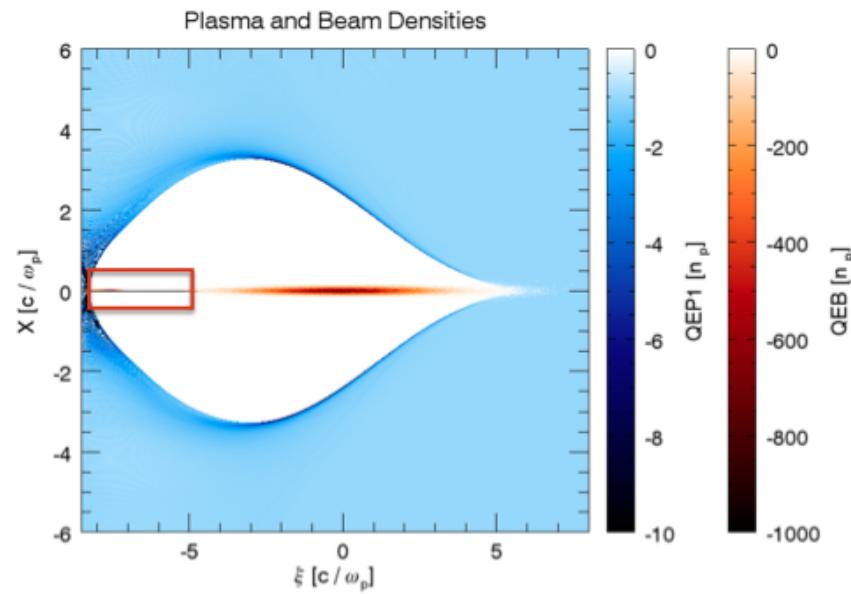


- Theory allows for designing highly efficient stages that maintain excellent beam quality.
- Theory allows for understanding how standard beams absorb energy of nonlinear wakes.
- Simulations for PWFA-LC showed ~50% energy transfer efficiency with >1% energy spread.

Need to explore the use of shaped beams to precisely flatten the wake

Big Challenge

Simulate smaller box with higher resolution: still big challenge

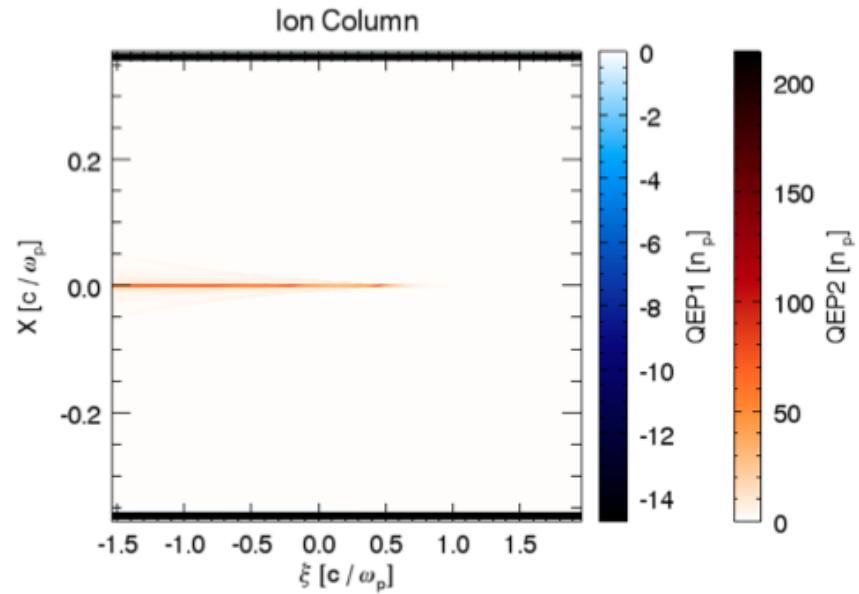


400 μm x 400 μm x 300 μm Box

16384 x 16384 x 2048 Cells

$$\Delta_{\perp} \approx 25 \text{ nm}$$

Rosenzwig et al PRL



12 μm x 12 μm x 60 μm Box

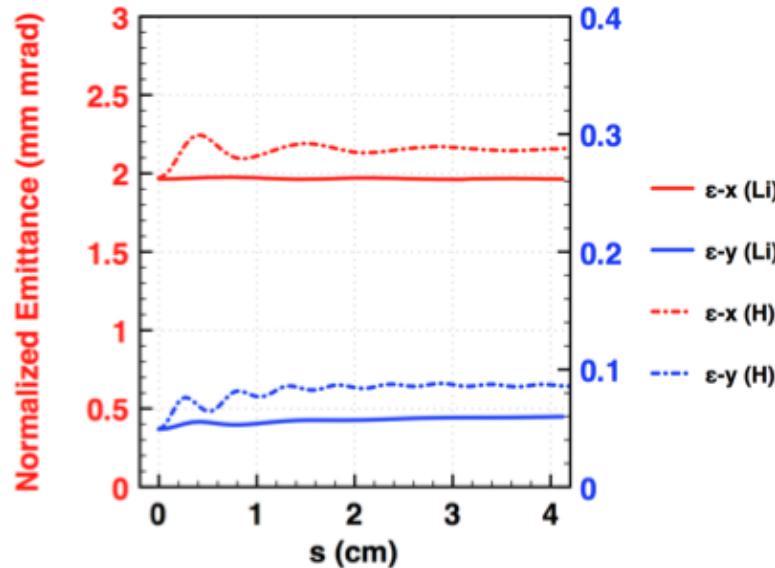
4096 x 4096 x 512 Cells

$$\Delta_{\perp} \approx 3 \text{ nm}$$

High Resolution Simulations show Emittance Increase (ion motion) may be manageable

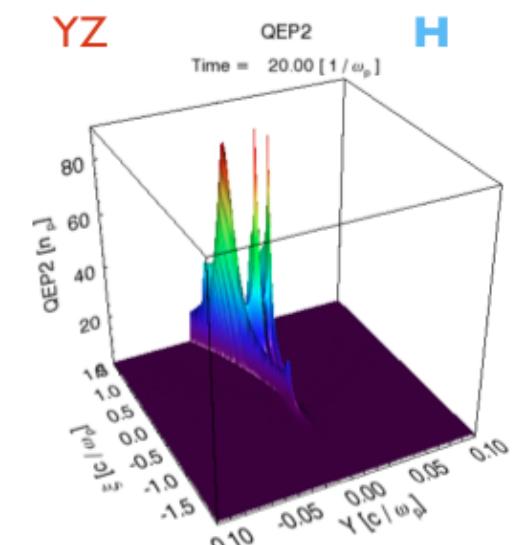
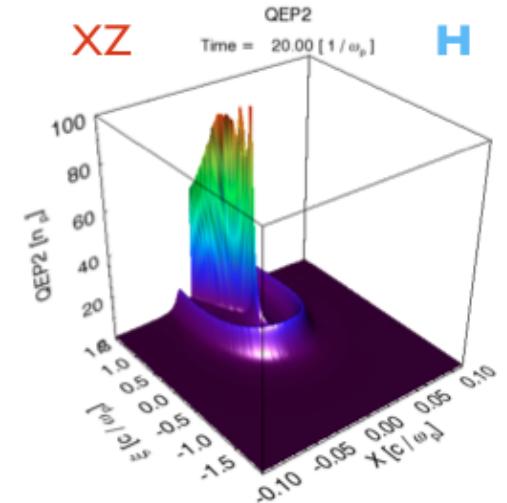
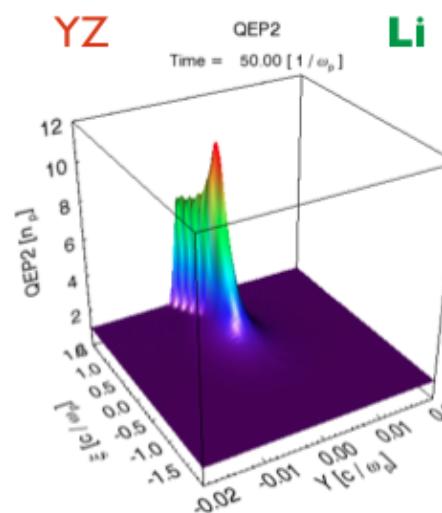
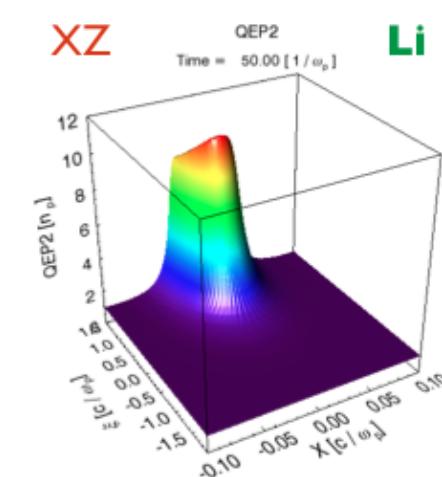
Trailing Beam: $\sigma_z = 10.0 \mu\text{m}$, $N = 1.0 \times 10^{10}$,

$$\begin{aligned}\sigma_x / \Delta_{\perp} &= 75.9 \\ \sigma_y / \Delta_{\perp} &= 12.0 \\ \sigma_x &= 0.463 \mu\text{m}, \varepsilon_{Nx} = 2.0 \text{ mm}\cdot\text{mrad}, \sigma_y = 0.0733 \mu\text{m}, \varepsilon_{Ny} = 0.05 \text{ mm}\cdot\text{mrad} \\ Y &= 48923.7 \text{ (25 GeV), Plasma Density : } 1.0 \times 10^{17} \text{ cm}^{-3}\end{aligned}$$



In Li, the emittance in x does not change, and in y direction it only increase by 20%.

In H, the emittance in x increase by 10%, and in y direction it increases by 70%.



What about Positrons?

Only place in the world to study this topic !!



$N = 2 \times 10^{10}$

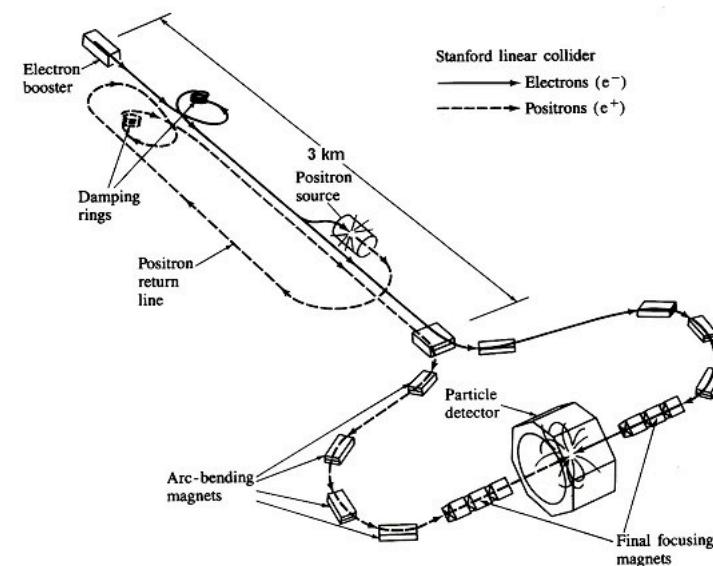
Energy 20 GeV

Rep Rate 60 HZ

Energy/pulse 150 J

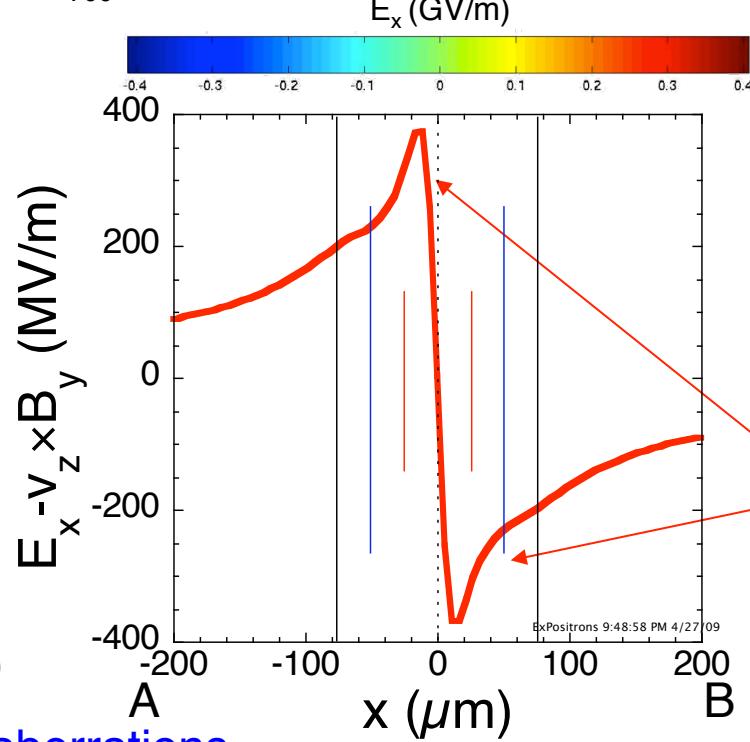
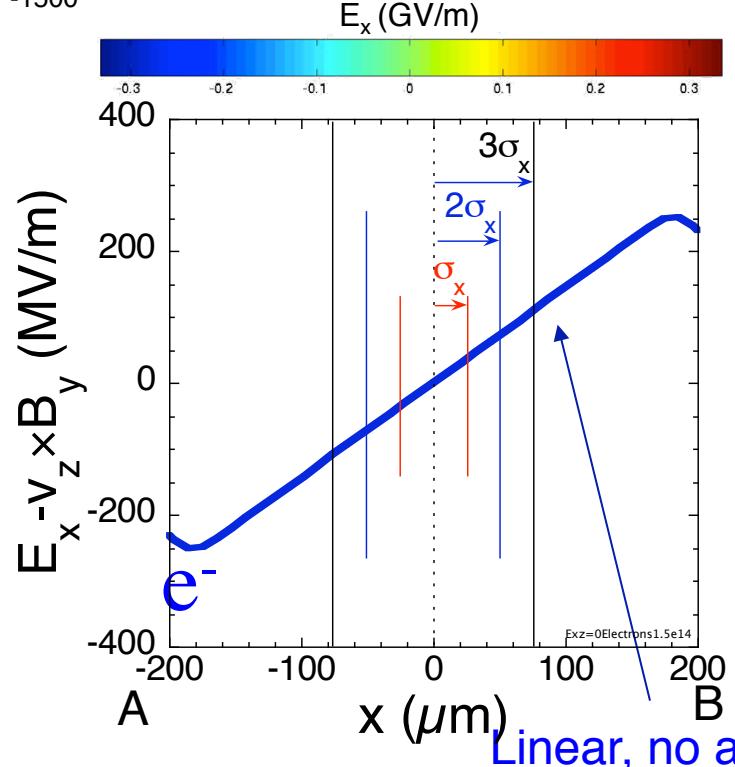
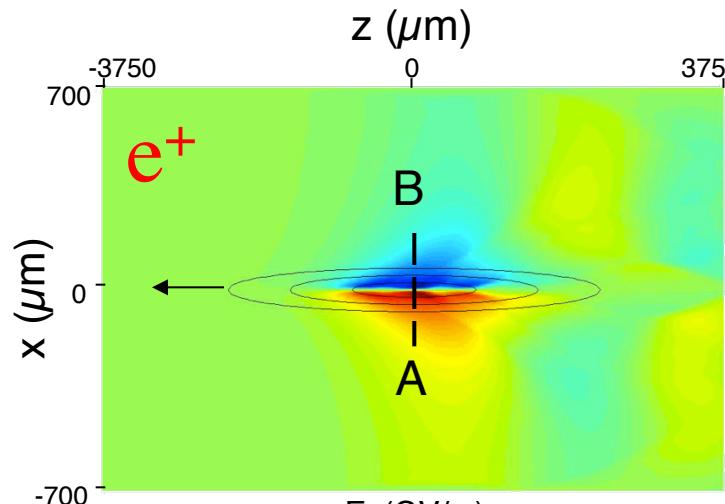
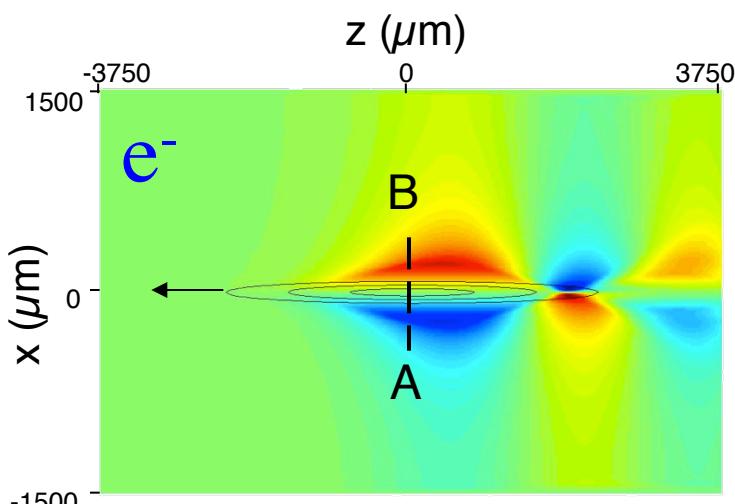
Focal Spot Size 30 micron

Pulse Width 15 micron compressed



e^- & e^+ Focusing Fields are quite different

UCLA



QuickPIC
 $\sigma_{x0}=\sigma_{y0}=25 \mu\text{m}$
 $\sigma_z=730 \mu\text{m}$
 $N=1.9 \times 10^{10} e^+/e^-$
 $n_e=1.5 \times 10^{14} \text{ cm}^{-3}$

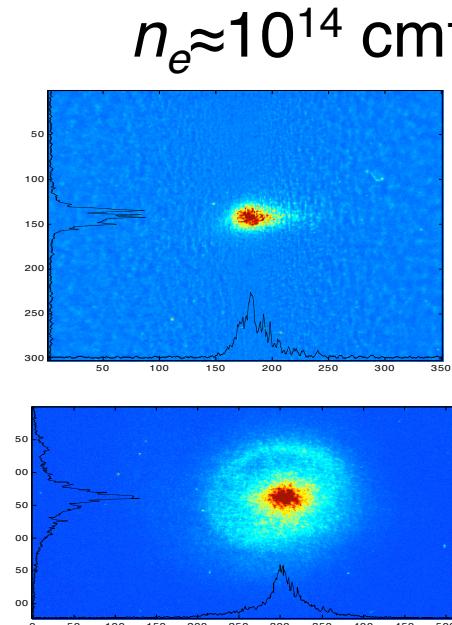
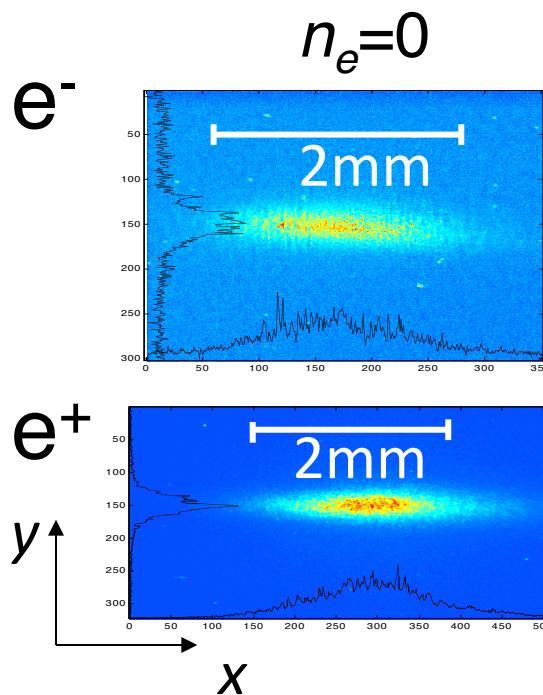
Non-linear,
aberrations

Linear, no aberrations

FOCUSING OF e^-/e^+ at FFTB

UCLA

- Beam images $\approx 1\text{m}$ from plasma exit ($\varepsilon_x \neq \varepsilon_y$)



- *Ideal Plasma Lens in Blow-Out Regime*
- *Plasma Lens with Aberrations (Halo Formation)*

How to minimize emittance growth of positrons due to nonlinear focusing fields?
-Explore wakes in hollow channels.

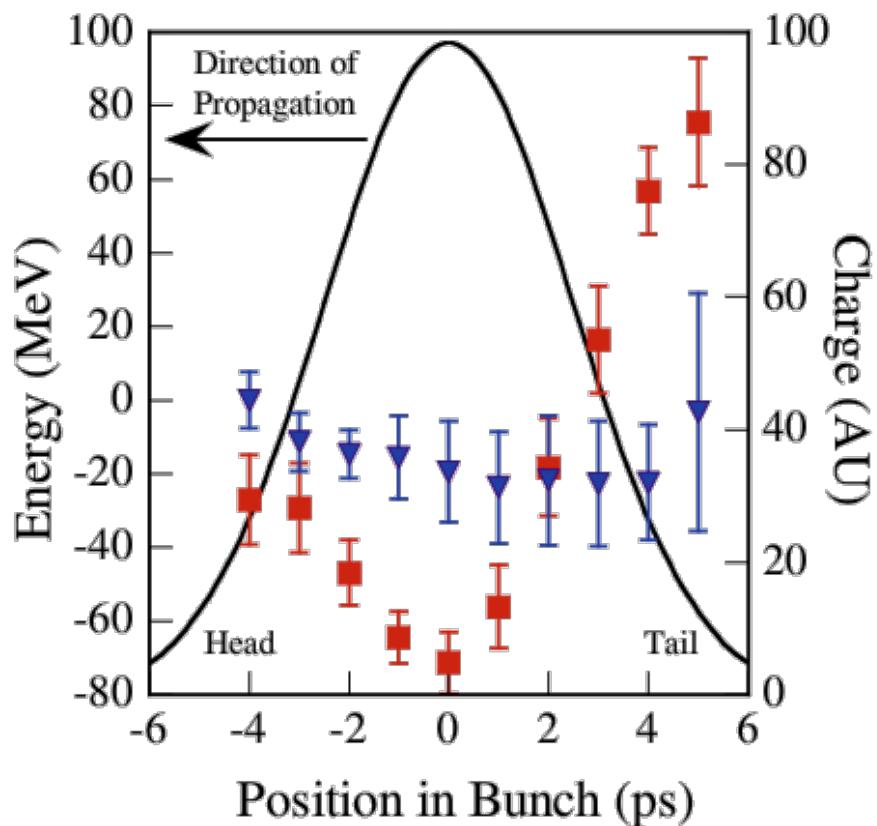
M.Hogan et al Phys. Rev. Letts. 2002)

P.Muggli et al Phys. Rev .Lett. 101 055001, (2008),

Positron Acceleration @ FFTB

Time Resolved Spectrum

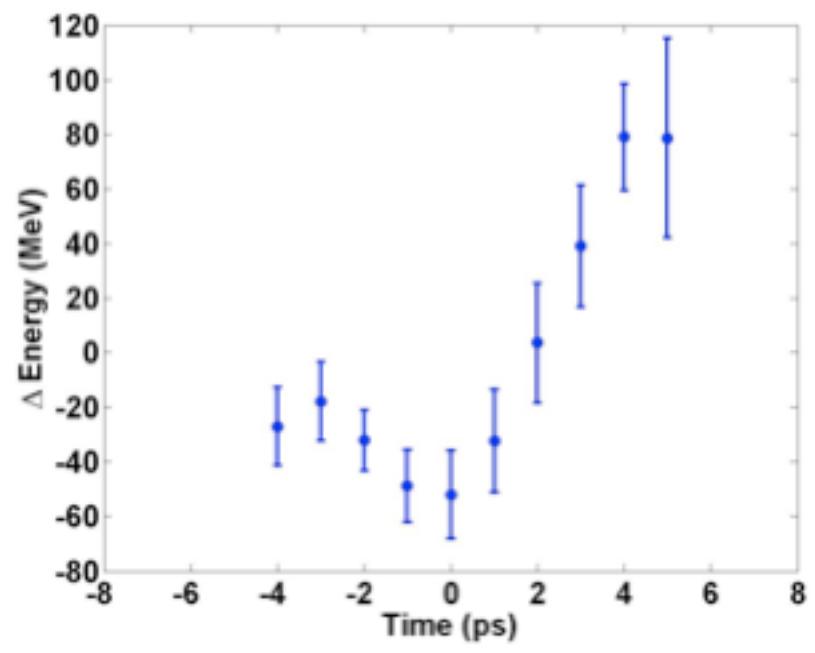
$N=1.2 \times 10^{10} e^+$, $n_e=1.8 \times 10^{14} \text{ cm}^{-3}$,
 $L=1.4 \text{ m}$



Experimental Measurement:

Peak Energy Gain

78 MeV
 $79 \pm 15 \text{ MeV}$



$5 \times 10^8 e^+$ in 1 ps bin at +4 ps

B.E. Blue et al., Phys. Rev. Lett. 90, 214801 (2003).

Results on High Gradient Acceleration of Positrons on FACET (Unpublished)

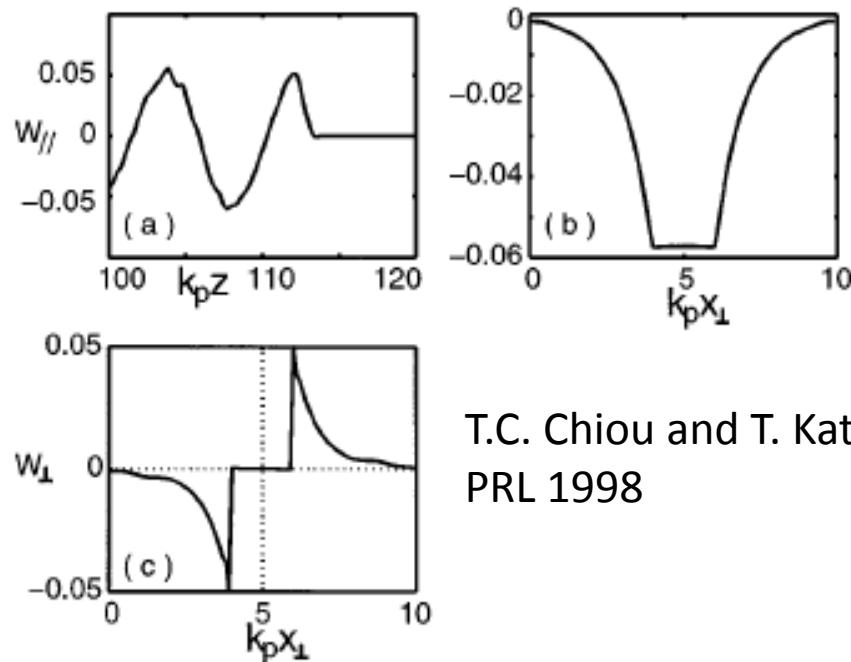
Redacted with apologies

Can we accelerate positrons in a wake driven by an electron bunch?

Wakes in Hollow Channel may be the solution FACET II – sailboat chicane needed

Goal :1 GeV in 1m with a narrow energy spread

E 200 Collaboration carried out first experiments on generation of hollow channels



Redacted with apologies

T.C. Chiou and T. Katsouleas
PRL 1998

Hollow Plasma Channels have uniform accelerating and zero focusing fields

Other approved and proposed experiments by UCLA PIs at FACET

E217 Ionization injection experiment Joshi Group Supported by NSF

E210 Trojan Horse Experiment Hidding, Rosenzweig et al

High transformer ratio experiment : Joshi Group FACET II

Ultra-low emittance electron beam generation: Joshi Group FACET II

Advanced Accelerator Research at UCLA Particle Beam Physics Laboratory (PBPL)

Prof. James Rosenzweig

Professor Pietro Musumeci

UCLA Dept. of Physics and Astronomy

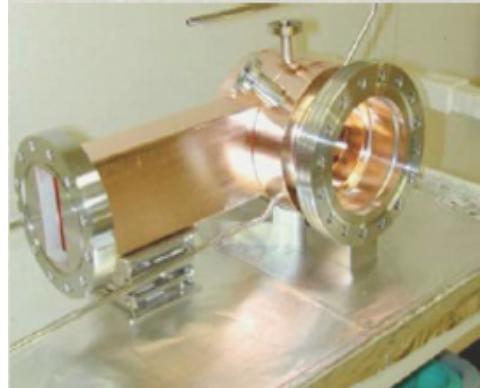
Backbone of PBPL research: advanced technology

- Connects advanced accelerators to conventional community
- Designed and built in-house
 - Design codes (students, engineers)
 - World-class shop

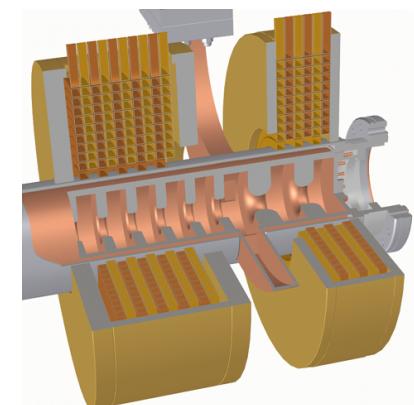
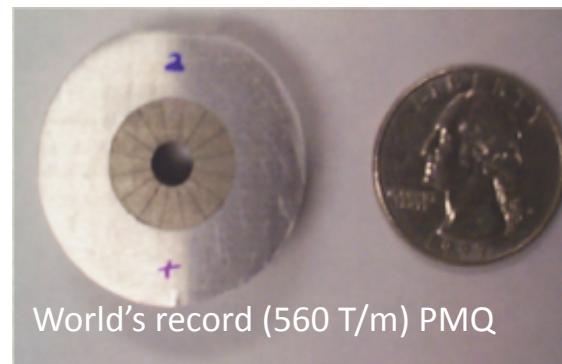
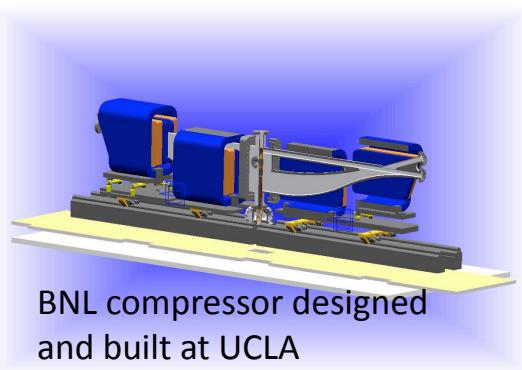
RF photoinjectors and deflectors

Magnets: chicanes, PMQs, undulators

- Led to spin off company: *RadiaBeam*



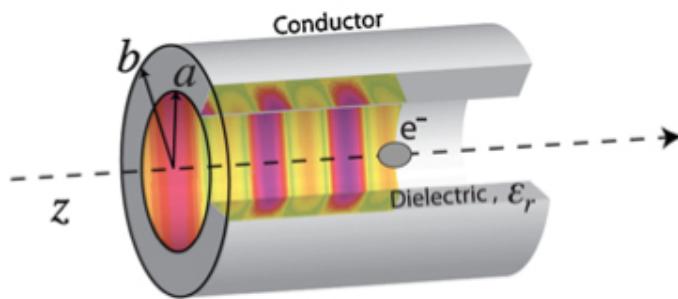
BNL/SLAC/UCLA 1.6 cell
RF gun (>12 made, *high impact*)



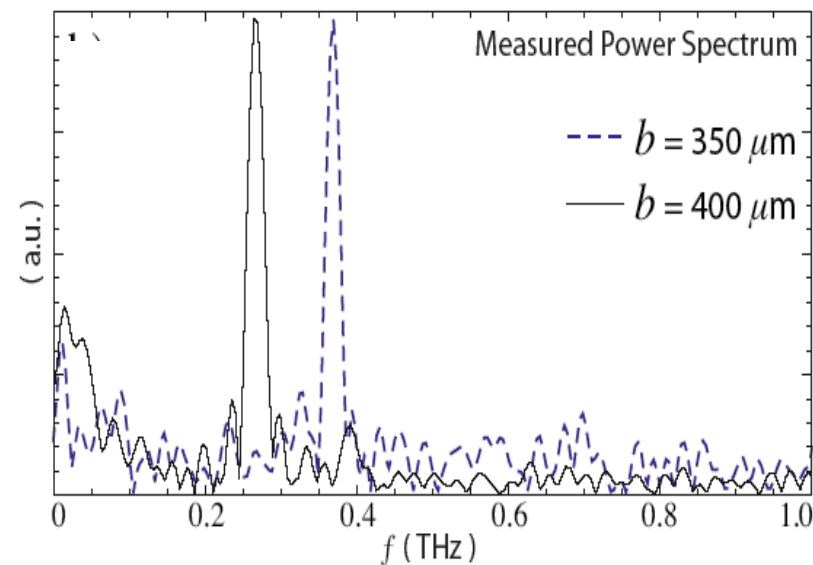
9 mm period cryoundulator (w/HZB)

PBPL Experimental Results I: Neptune (on-campus) THz from DWA

- *Extreme narrow band* THz source from dielectric wakefields: coherent Cerenkov radiation (CCR)
- Scalable to very high power (FACET)
- Established new measurement tools



Dielectric wakefield
accelerator (DWA)

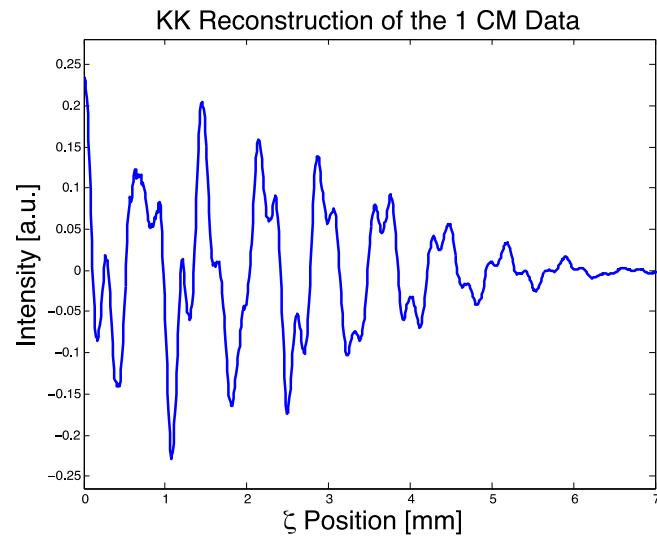


A. Cook, et al., Phys. Rev. Lett.
103, 095003 (2009)

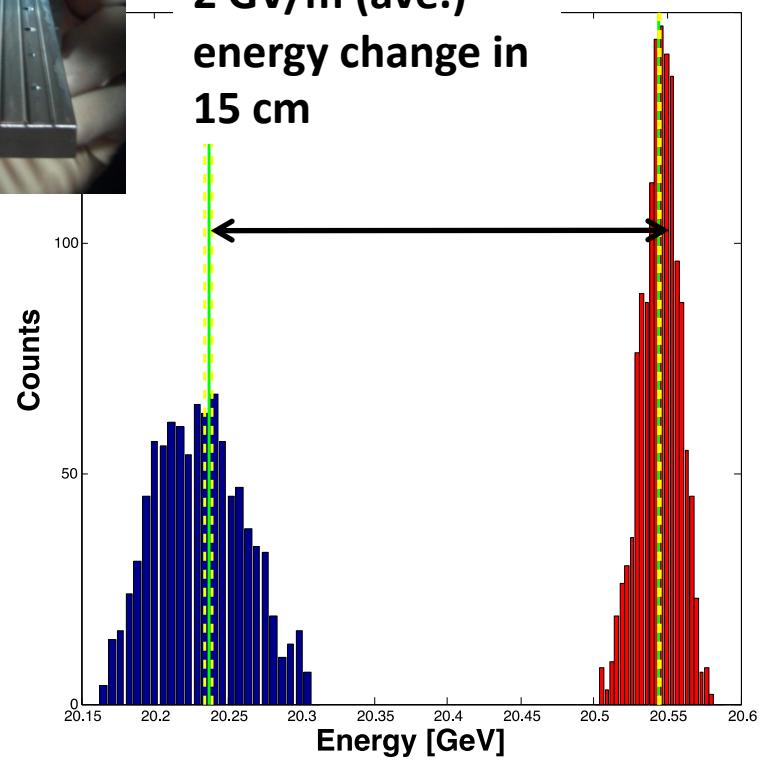
Two different tubes giving narrow band THz

Recent Results: GV/m DWA demonstrations at FACET

- New method for wake resolution: Kramers-Kronig reconstruction



2 GV/m (ave.)
energy change in
15 cm



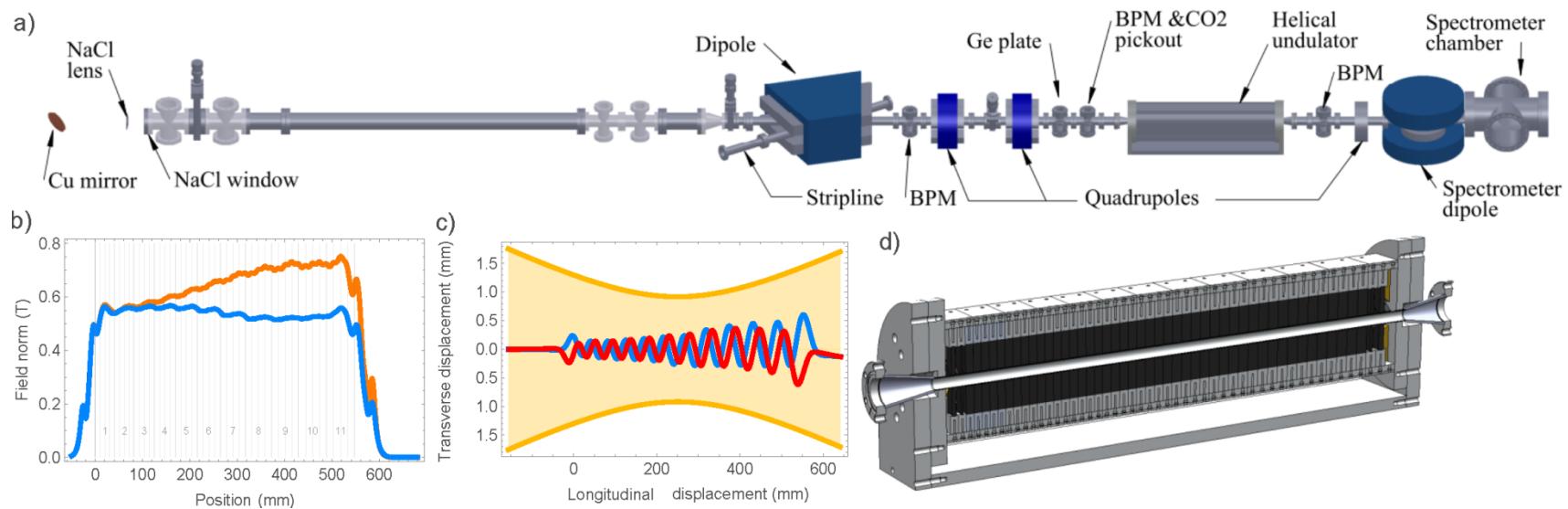
- Peak wake of 3 GV/m!
- *No structure damage*
- Near 1J of THz CCR

Centroid shifts of the beam

Rubicon IFEL at ATF: Musumeci Group

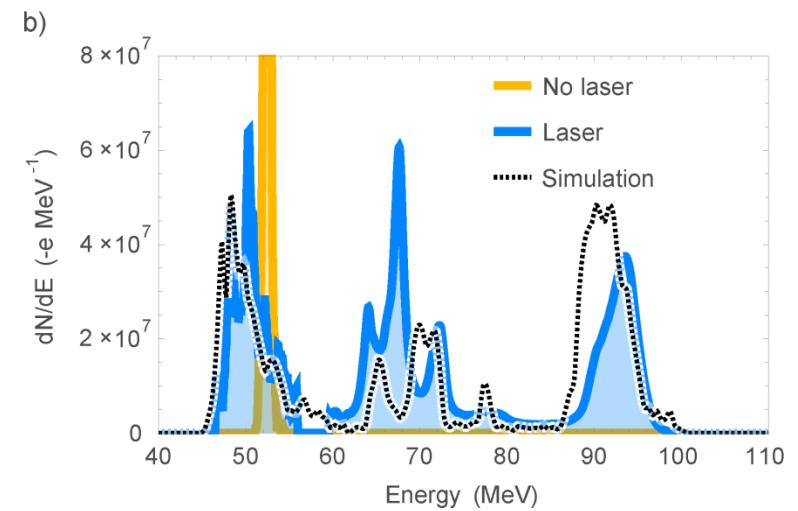
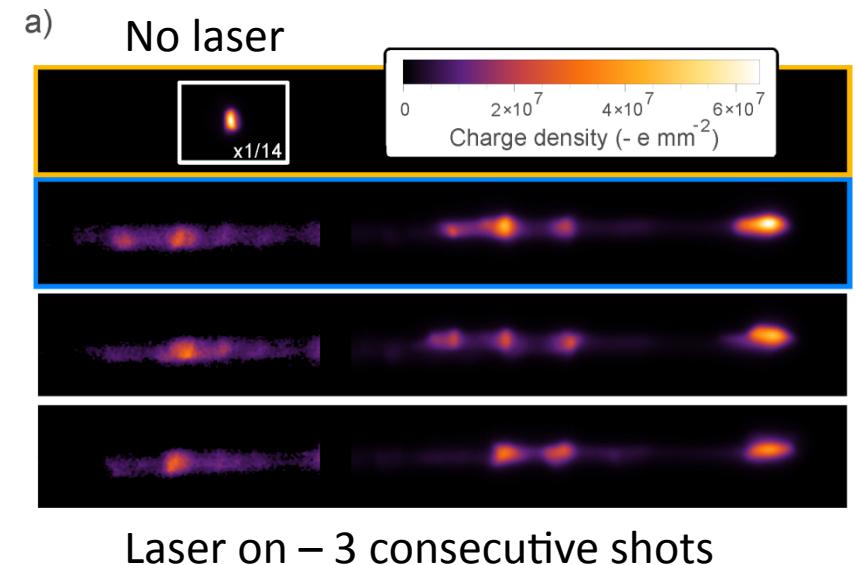
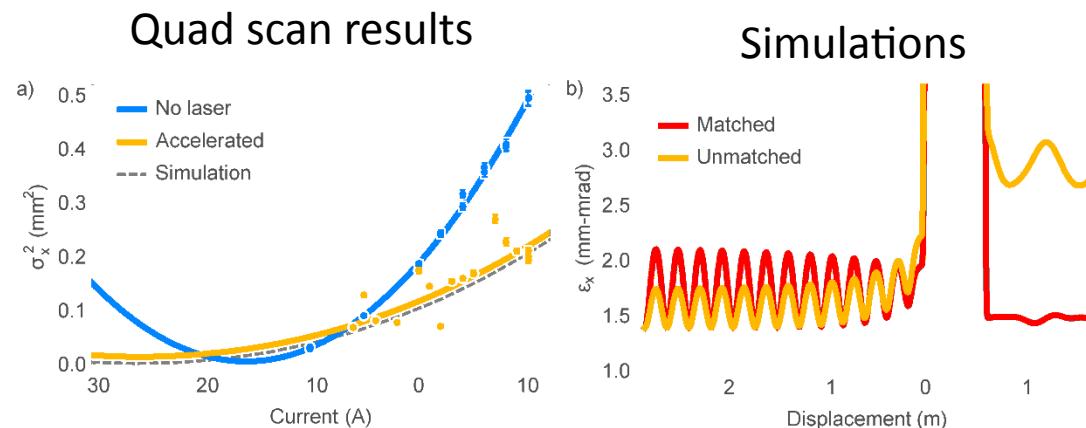
- Helical geometry high gain high gradient IFEL
- First strongly tapered helical undulator
- Two different tapering used
 - Demonstrate control of the final beam properties

Input e-beam energy	50 Mev
Average accelerating gradient	124 MV/m
Laser wavelength	10.3 μ m
Laser power	300 GW
Laser focal spot size (w)	980 μ m
Laser Rayleigh range	25 cm
Undulator length	54 cm
Undulator period	4 – 6 cm
Magnetic field amplitude	5.2 – 7.7 kG



IFEL Produces high quality output beams

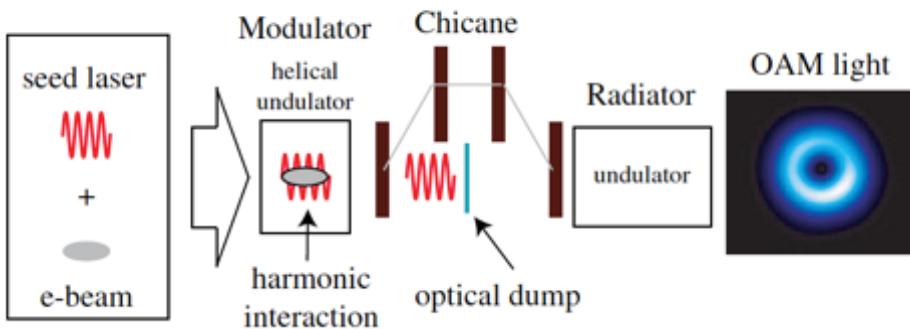
- 93 MeV – 1.8 % energy spread
- Very reproducible (mean energy std < 1.5 %)
- Laser intensity 5 orders of magnitude lower than LWFA
- Good agreement with experimental prediction
- Emittance measurement
 - Quad scan on energy dispersed beam
 - Emittance growth is due to mismatching in the undulator



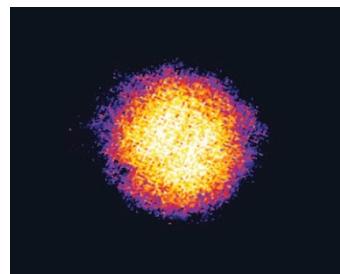
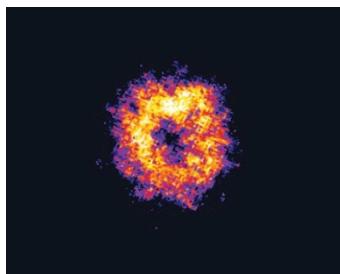
Many other accomplishments of the PBPL Group



Advanced dielectric structures:
photonic band gap woodpile
Bragg reflector structure



Electron Micro bunching Using
Helical Undulator for OAM photon
Modes.



Linear and nonlinear Inverse Compton
Scattering at ATF

Summary of UCLA AA Research

- 1) Extremely strong, and broad effort in advanced accelerator field
- 2) Attracts top students
- 3) Birthplace of numerous new ideas
- 4) Students have state-of-the art facilities for research
- 5) Very strong computer simulations group
- 6) UCLA has been the top user of FFTB, ATF and FACET
- 7) UCLA is committed to push AA concepts such as PWFA, dielectric acceleration and IFEL with a goal of developing a disruptive technology for colliders and 5th generation light sources.

Need National User facilities such as FACET, ATF, FACET II and ATF II for maintaining the US leadership in this field.
U.S. users need access to a BELLA class user facility to contribute to LWFA effort.

- BACK UP SLIDES

Linear wake fields driven by e^- and e^+ beams

Plasma Density

Accelerating Field

Focusing Field

 UCLA

 e^- Beam

$$n_b \ll n_p$$

 e^+ Beam

$$n_b = n_0 e^{\frac{-r^2}{2\sigma_r^2}} e^{\frac{-z^2}{2\sigma_z^2}}$$

$$\sigma_r = 1.0 k_p^{-1}$$

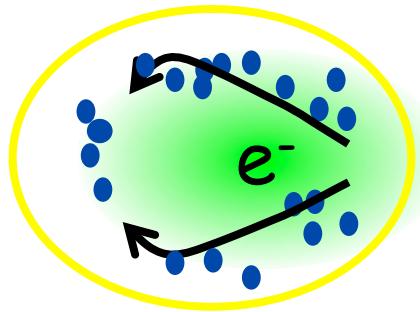
$$\sigma_z = 1.0 k_p^{-1}$$

QuickPIC simulations

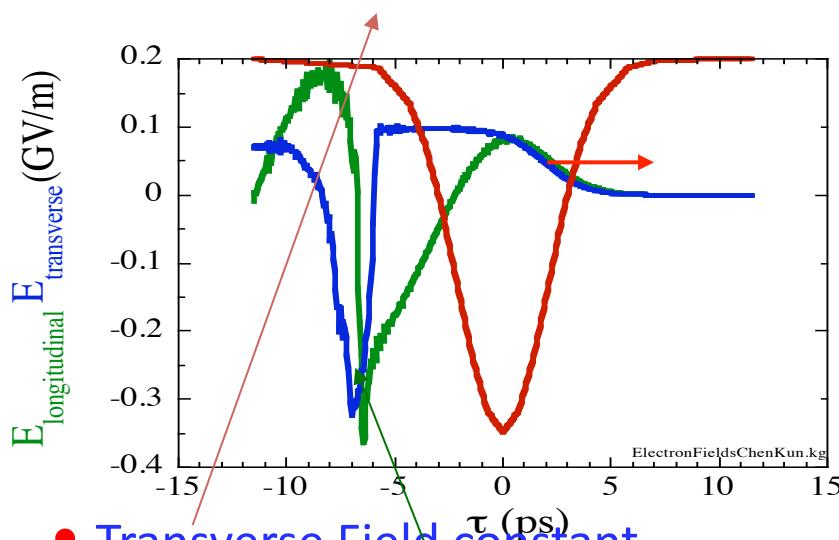
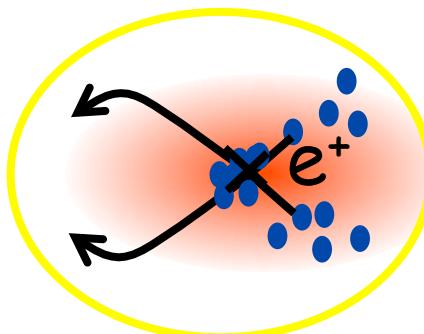
By Weiming An and Warren B. Mori UCLA

WAKEFIELD FIELDS for e^- & e^+ very different in Nonlinear Regime

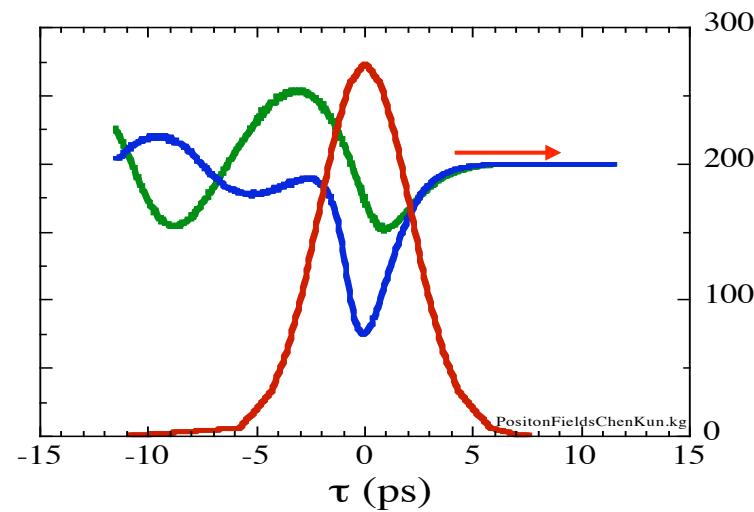
UCLA



$n_e = 1.5 \times 10^{14} \text{ cm}^{-3}$
homogeneous, QUICKPIC



- Transverse Field constant
After Plasma electrons Blown-Out
- Longitudinal field Shows
Accelerating “Spike”



- Fields vary along r, stronger
- Less Acceleration

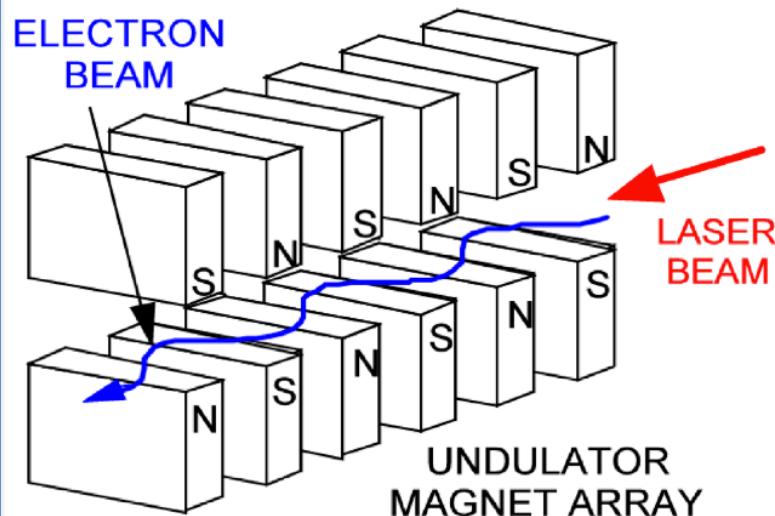
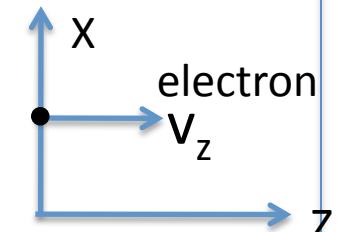
Beam Current (A)

Far Field Acceleration

UCLA

Accelerating beam far from material boundary

$d\gamma/dz = ev \cdot E/(mc^3)$, since laser field and particle velocity are orthogonal, either induce a z component to the field or induce a transverse velocity component to the particle: $v_z E_z$ or $v_{x(\text{perp})} E_{\text{perp}}$



Inverse Free Electron Laser

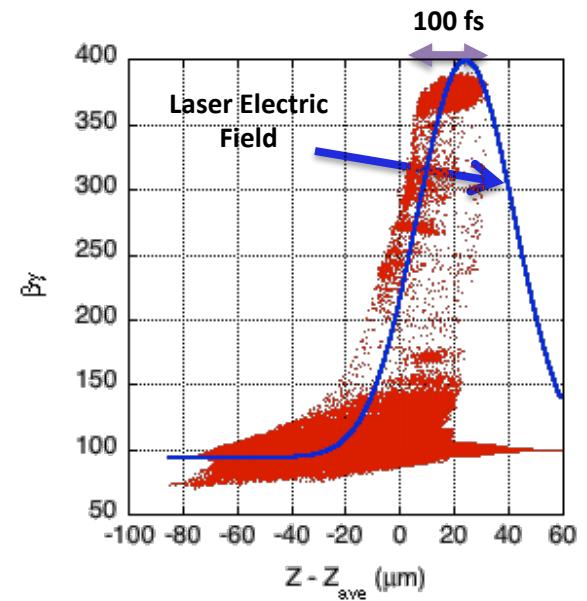
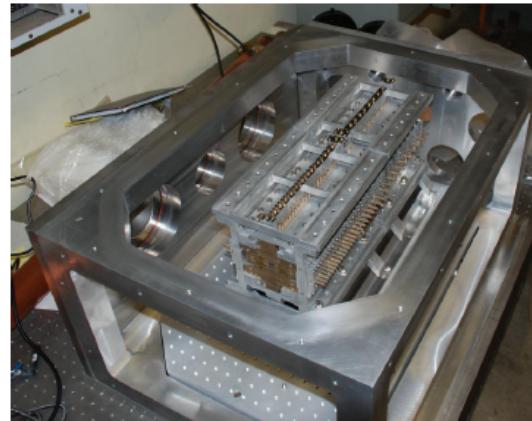
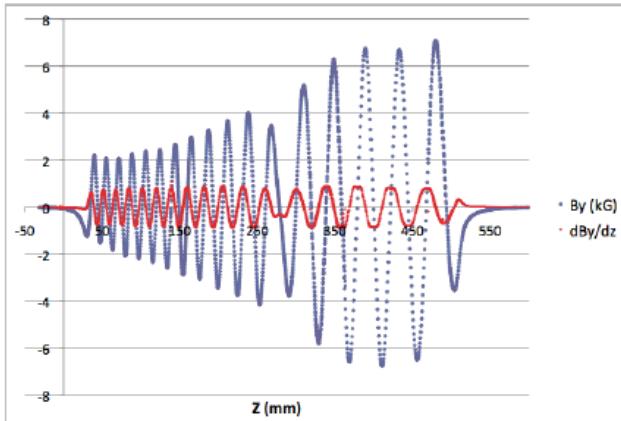
$$\frac{d\gamma}{dz} = \frac{2\pi a_s a_w}{\gamma \lambda_s} \sin\Phi,$$

$$v_\phi = \omega/(k_w + k_l) < c$$

Synchrotron Loss limits Acc'n

LLNL Ti:Sa IFEL accelerator

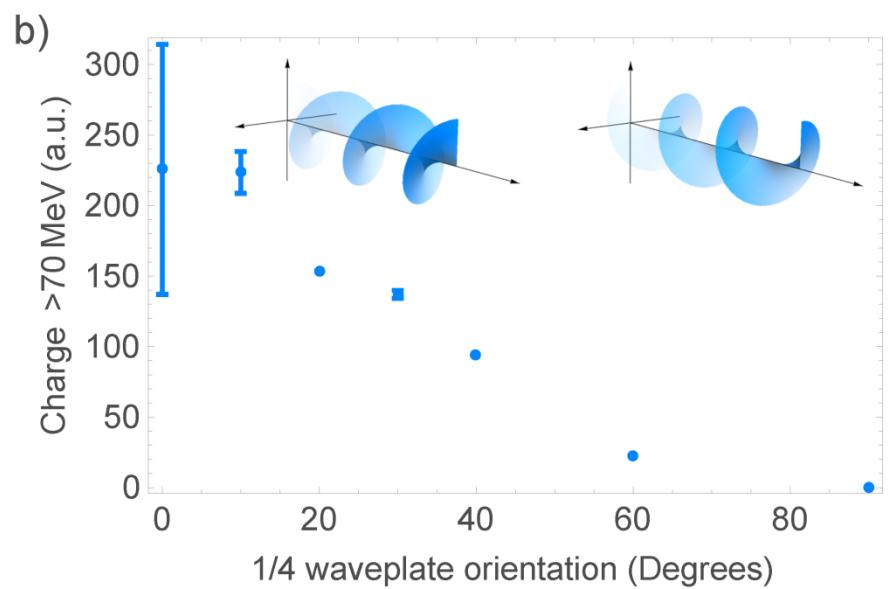
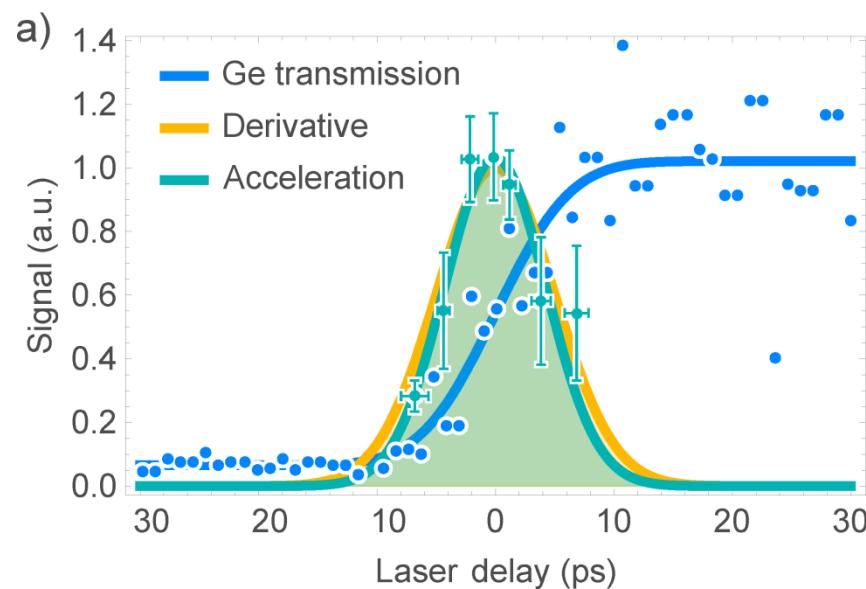
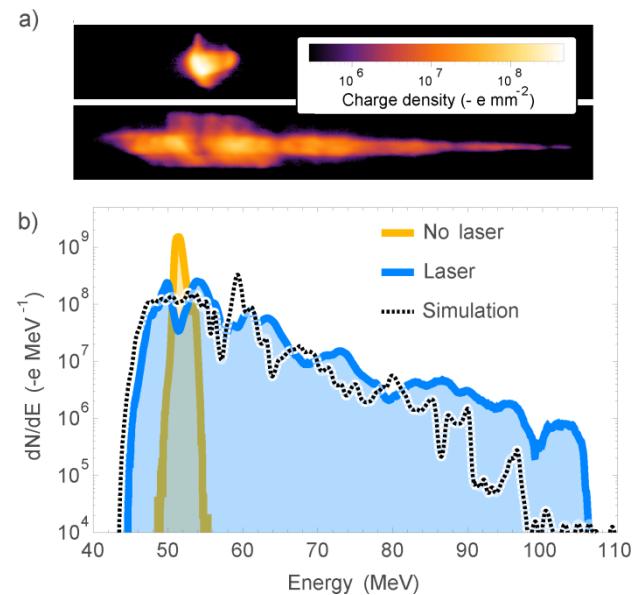
- First TW-class laser driven IFEL
- Strongly tapered Kurchatov undulator for diffraction-dominated interaction
- Short pulses (sub-ps) interaction
- Improved modeling of the interaction:
 - Time-dependent effects
 - Higher order laser modes
 - Space charge



Design Parameters	Initial	Final
Period	1.5 cm	5.0 cm
Peak K parameter	0.2	2.8
Neptune Energies	14 MeV	52 MeV
LLNL Energies	50 MeV	200 MeV

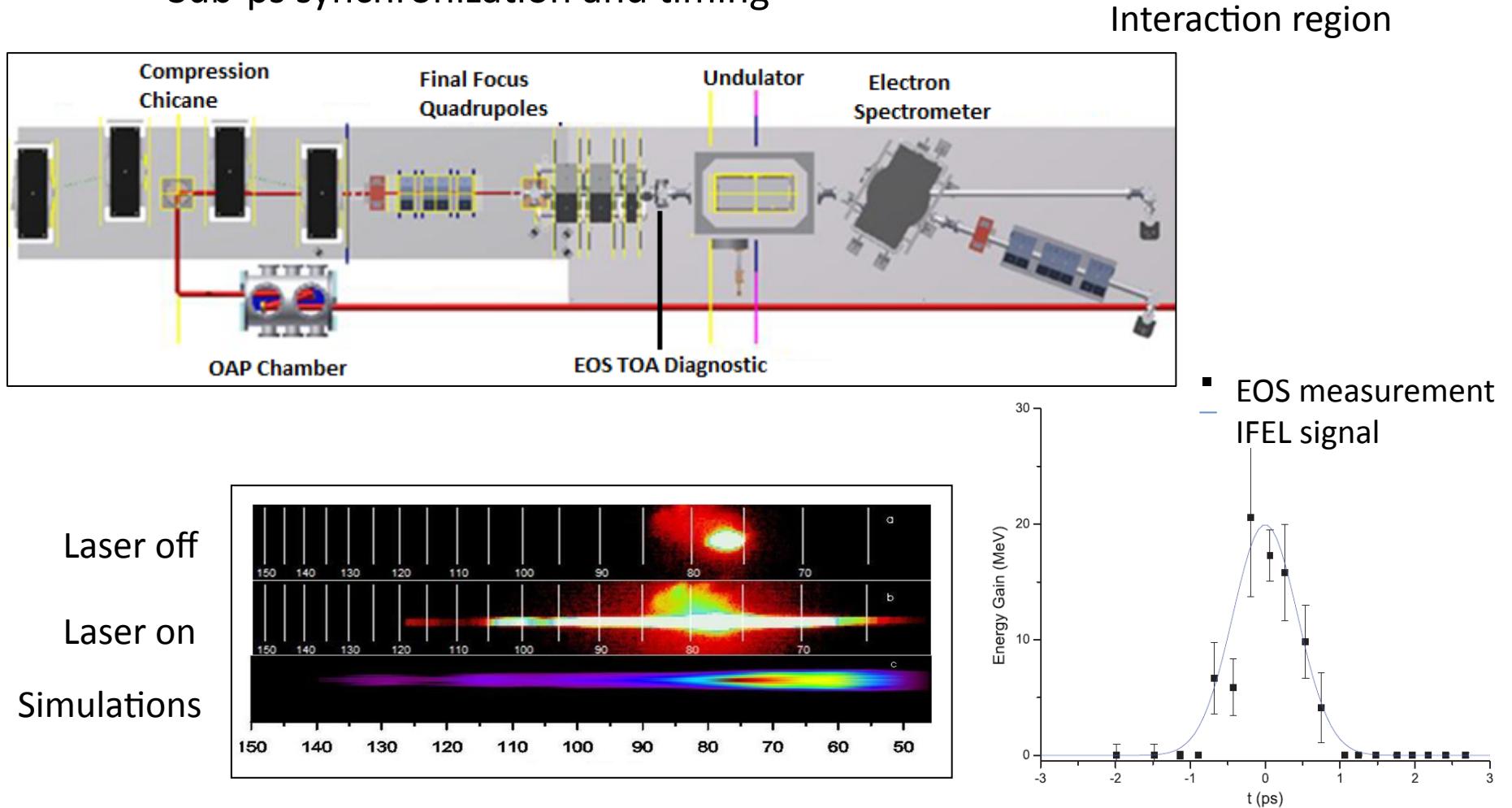
High gradient tapering scheme

- 50 MeV energy gain
- 100 MV/m gradient
- Timing
- Polarization studies



Short pulse laser driven IFEL

- 77 MeV – 122 MeV in 22 cm
- > 200 MV/m gradient !
- Sub-ps synchronization and timing

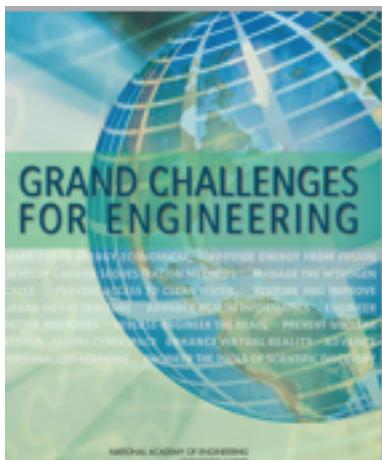


P5 and NAE have both Articulated the Grand Challenge for HEP



P5 Report: Building for Discovery **In Scenario C, the first thrust is:**

“Going much further , however, requires changing the capability-cost curve of accelerators, which can only happen with an aggressive, sustained, and imaginative R&D program. **A primary goal, therefore, is the ability to build the future generation accelerators at dramatically lower cost.** ...For e^+e^- colliders, the primary goals are improving the accelerating gradient and lowering the power consumption”

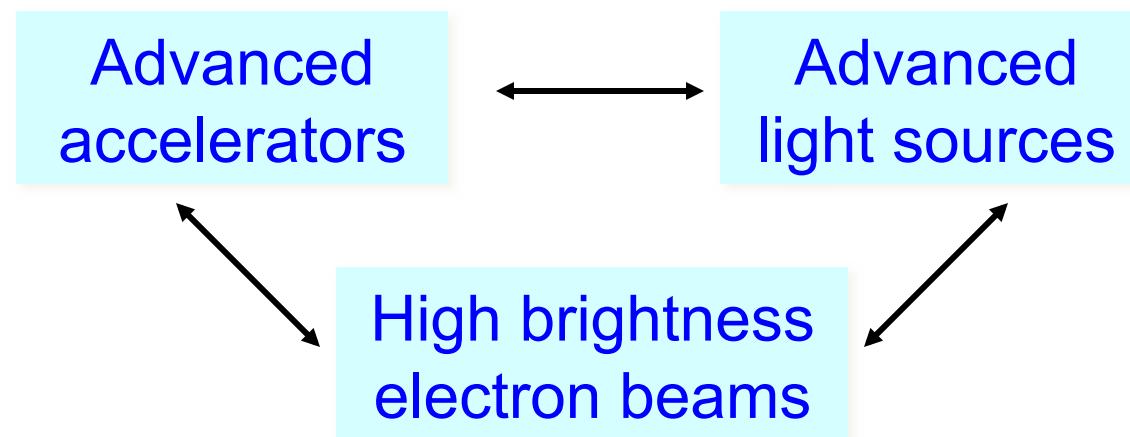


NAE Grand Challenges for Engineering **Engineer Tools of Scientific Discovery**

“..engineers will be able to devise smaller, cheaper but more powerful atom smashers, enabling physicists to explore realms beyond the reach of current technology.”

The Particle Beam Physics Lab (PBPL)

- Group built upon three research thrusts



- Strong connections between all areas
 - Common themes: *multi-disciplinary*, high energy density (relativistic) interactions, ultra-fast systems
- Fundamental beam physics and advanced technology underpins other two areas
- Now moving to *applications*: inverse Compton, e- diffraction